Note on Drexel tests of the IMB R1408 PMTs used in the inner veto of both far and near detectors of the Double Chooz experiment

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Abstract

This report is related to the testing performed at Drexel University of 250 R1408 PMTs. Based on this testing, 156 R1408 PMTs were chosen to be used in the inner veto of the detectors of the Double Chooz experiment[1].

Contents

1 Introduction

More than 260 R1408 PMTs were obtained from UC Irvine, these PMTs were used in IMB[2] and SuperKamoika[3] experiments. These 13 stages, 8 inches, R1408 PMTs don't have a single photo-electron peak and the cause of that is expected to be due to their venetian blind dynodes. The aim of the testing performed at Drexel University was to be sure that most of these PMTs are still working correctly, and then make a choice of 156 of them. The testing concerned the determination of the high voltage corresponding to a gain of $\sim 10^7$, saturation level and the dark noise rate. To make this testing different calibration techniques were used, the photo-statistics and the light pulser methods. Most of these PMTs came with their original linear bases, a first testing of 250 PMTs was made with these bases, after that a new testing was performed with a new tapered bases.

2 Calibration techniques

2.1 The Photo-statistics method

In this section I will summarize the principle of the Photo-statistics method. With an ADC we are not measuring a charge q directly, but an ADC value a that is related to q by:

$$a = q + a_p \tag{1}$$

Where a_p is the ADC pedestal. As it can be demonstrated, the gain can be extracted via the following relation:

$$\frac{d\sigma_a^2}{d\mu_a} = 2Ge \tag{2}$$

Where μ_a and σ_a are the mean and the variance of ADC charge distribution, and Ge is the ADC count per photo-electron, called also gain/channel, with $e = 1.6\ 10^{-19}C$. All we need is to take a series of LED/laser runs at varying light levels, and for each of these runs to measure the statistical mean and variance of spectra as shown in figure 1, after that plot the variance versus the mean, and fit the linear region with a straight line like in figure 2. The gain will be extracted from the slope of the line following the equation 2. One important feature of this method is it is electronics pedestal independent, to get the absolute gain one needs to multiply the gain/channel by the ADC coefficient calibration. To obtain the saturation level I consider the point after the linearity of PMT response is broken, the ratio of the ADC mean at the

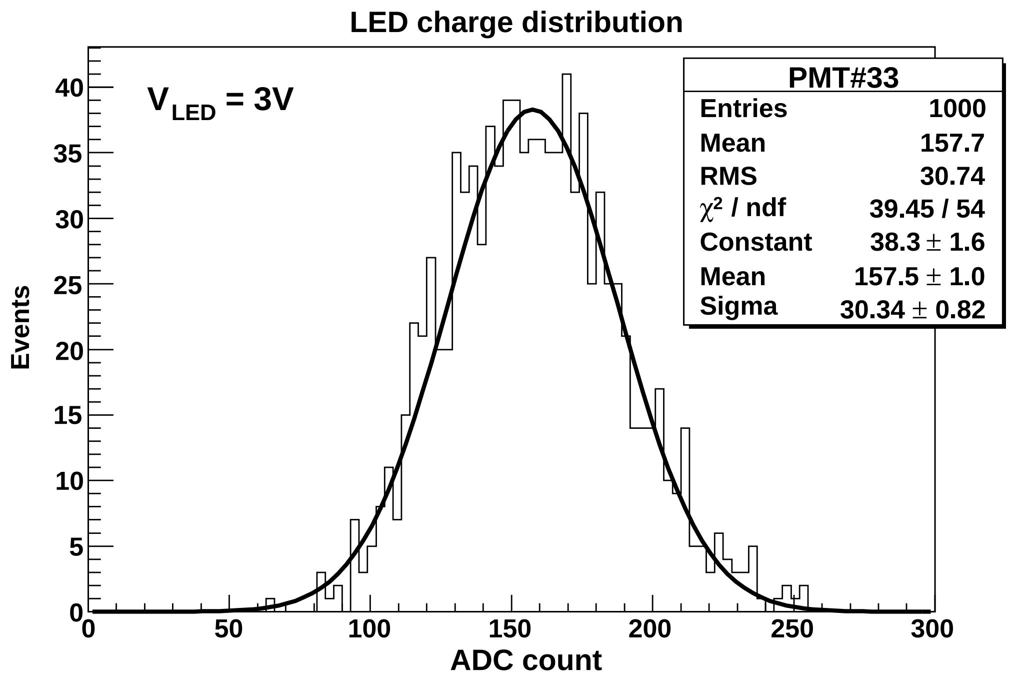

Figure 1: ADC distribution for LED pulses.

considered point and the gain/channel gives the saturation level in the number of photo-electrons, figure 2 shows an example of this procedure. Since the saturation level is determined by eyes it becomes human dependent, two measurements performed by two different persons may give different values.

2.2 The light pulser method

2.2.1 Characteristics of the light pulser

An ^{241}Am α source is fixed on a NaI crystal. The choice of the crystal is very important in the way that it will let the emitted α particles to have a uniform energy loss which allows the production of monochromatic photons inside the scintillator. The scintillator crystal chosen for the present measurements is NaI(Tl), The α peak appears at an equivalent γ ray energy of 2.6 MeV. The table 1 summarizes the characteristics of the used Am pulser.

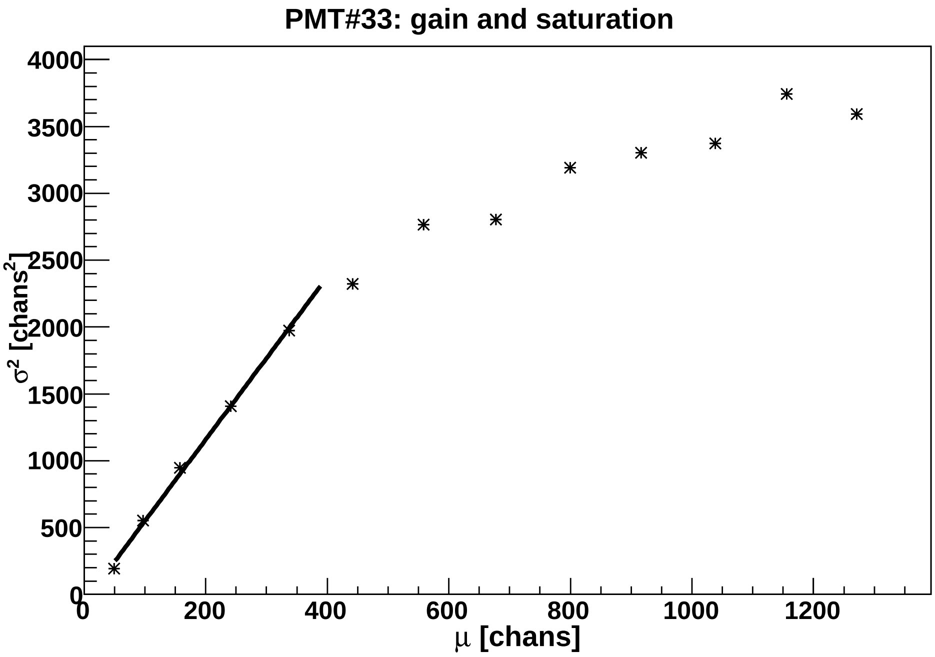

Figure 2: ADC variance(σ^2) versus ADC mean(μ) for a variety pulse heights. The slope of the fit of the linear region gives the gain, and the $saturation\ level = 441/3.04 = 145\ photo - electrons$.

2.2.2 The Procedure of the gain determination

I started by testing with the photo-statistics method a set of 8 PMTs from which I selected the most convenient one from the point of view of low dark noise rate and high saturation level. The chosen PMT became the PMT reference for the measurements with the Am pulser. The figure 3 shows the evolution of the maximum pulse of the PMT reference with the applied high voltage. The maximum pulse increase in exponential way with increasing applied high voltage. One important parameter is the value of the trigger which need to be set properly for accurate determination of the maximum pulse. The figure 4 shows the variation of the threshold value with variable high voltage. To obtain the maximum pulse I used a scope tuned to its maximum averaging value.

The photo-statistics method gave the high voltage corresponding to the gain $\sim 10^7$ for the PMT reference at 1375 Volts, the maximum pulse corresponding to this high voltage is 720 mV as we can see from the figure 3. To get the high voltage corresponding to the gain $\sim 10^7$ for the other PMTs, I just

Isotope	^{241}Am
Half-life	458 years
Emission	α particles, 59.5 keV Np L-X-rays
Gamma Equivalent Energy (G.E.E)	1.5 to 3.5 MeV
Tolerance on G.E.E	$\pm15\%$
Count Rate	10 to 2000 cps
FWHM:	3 to 5%
Temperature Range	$4°C$ to $40°C$

Table 1: Properties of the Am pulser

increased the value of the high voltage applied to each one until I obtained the maximum pulse of $\approx 720\,\mathrm{mV}$, then I considered these PMTs tuned to the appropriate gain value.
To keep the light pulser at fixed distance from the photocathod, the ^{241}Am source was fixed on the top of a funnel.

3 PMTs testing results

In this section I will present the procedure and the results of the testing of 250 PMTs, this testing was made with the original old linear bases.
I used the Am^{241} light pulser to determine the high voltage corresponding to the gain 10^7, the result is shown in the figure 5. One time I know the desired high voltage I used the photo-statistics method to cross check the PMTs gain, to this aim I put each PMT under the predetermined high voltage, inside the dark box, with an LED connected to a fast pulser. The trigger output of the pulser was sent to Lecroy 222 Gate and Delay units, first to set a delay, and then to produce a 200 ns gate that enclosed the PMT pulse that occurred when the LED was flashed, the used setup is shown in figure 6. The PMT signal was sent to a Lecroy 2249W ADC, with the gate coming from the 200 ns gate and delay output. The LED was flashed at 20 Hz at a variety of driving voltages from 2V to 8V, all with very narrow (20 ns) driving pulse widths. In all cases, the PMT pulse was observed on an oscilloscope to be completely contained within the 200ns ADC gate. For each of the ADC distributions, the mean and variance was calculated, as discussed in section 2, and the ADC variances were plotted as a function of the the ADC means which let to obtain the gain(figure 7) and the saturation level(figure 8). To measure the dark noise rate the PMTs were put under high voltage during 12 hours, the signal from the PMT was amplified 100 times and then send

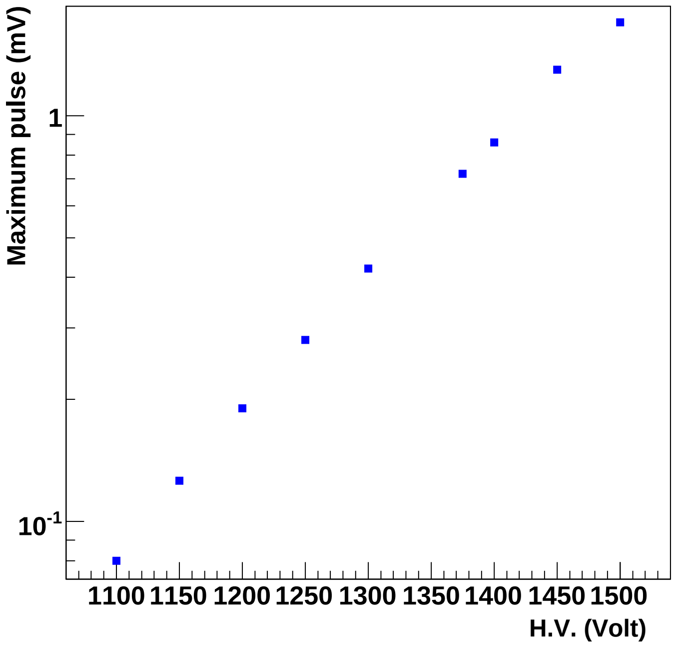

Figure 3: Evolution of the maximum pulse with the applied high voltage for the PMT reference (using the original linear base).

to the input of a LeCroy Model 821 quad discriminator, the threshold of the discriminator was set to 2mV, the output of the discriminator was sent to the counter. The temperature inside the dark box was measured around $19°C$. The measured dark noise rate is shown in the figure 9, the figure 10 shows the corresponding threshold in single photo-electron, to evaluate this threshold we need to remember that the dark noise rate is due to the production of some number, n, of electrons inside the PMT, without any lighting of the photocathod. These n produced electrons create a current I_0 in the out put of the PMT equal to $\frac{n \times e \times G}{t_W}$, where $e = 1.6\ 10^{-19} C,\ t_W$ is the FWHM of the pulse (measured with a scope), and G is the PMT gain. We can write I_0 as following: $I_0 = \frac{V}{Z_0}$, where V_0 is the potential(high of the pulse) and Z_0 is the impedance of the cable, this lets us to write n as function of V as following:

$$n = \frac{V \times t_W}{e \times Z_0 \times G} \tag{3}$$

The equation 3 link the number of the electrons n to their potential V, in the other words this formula lets us to translate the threshold from the

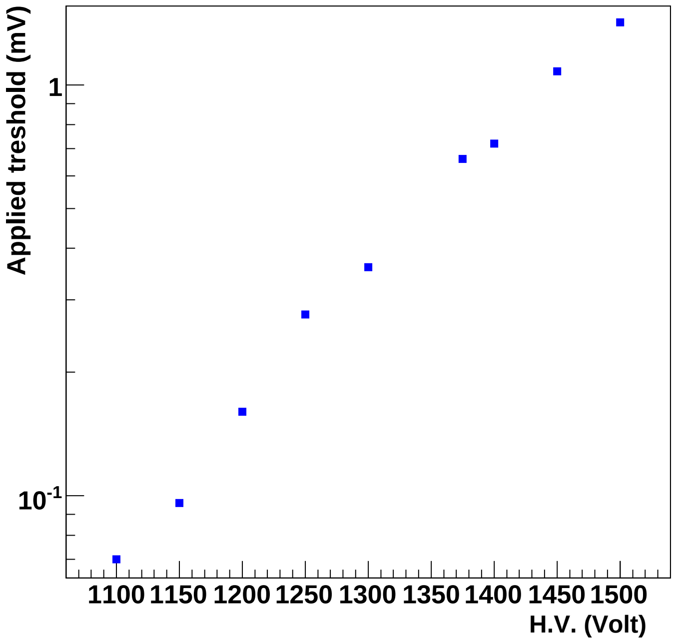

Figure 4: Evolution of the Threshold value with the applied high voltage for the PMT reference(using the original linear base).

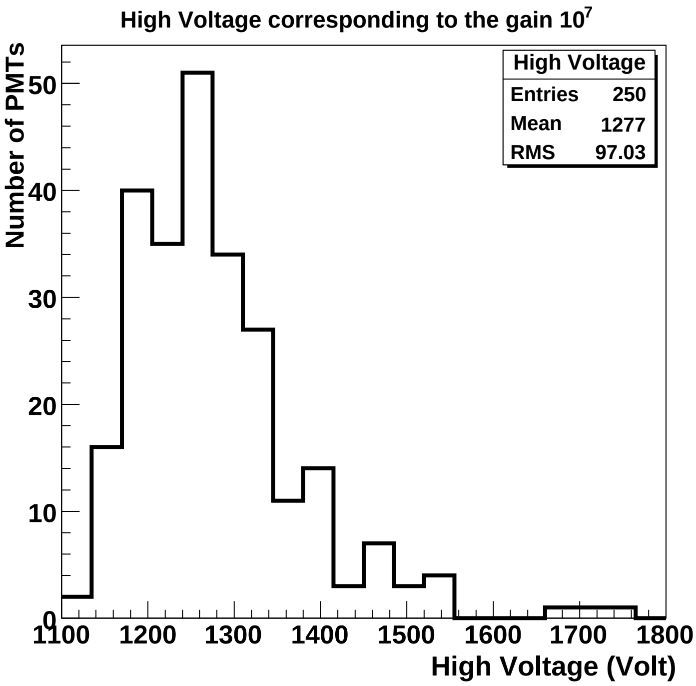

Figure 5: The high voltage corresponding to the gain $\sim 10^7$ obtained with the light pulser(using the original linear bases).

volt into term of number of electrons, in our case V was set to 2mV and $Z_0 = 50\Omega$.

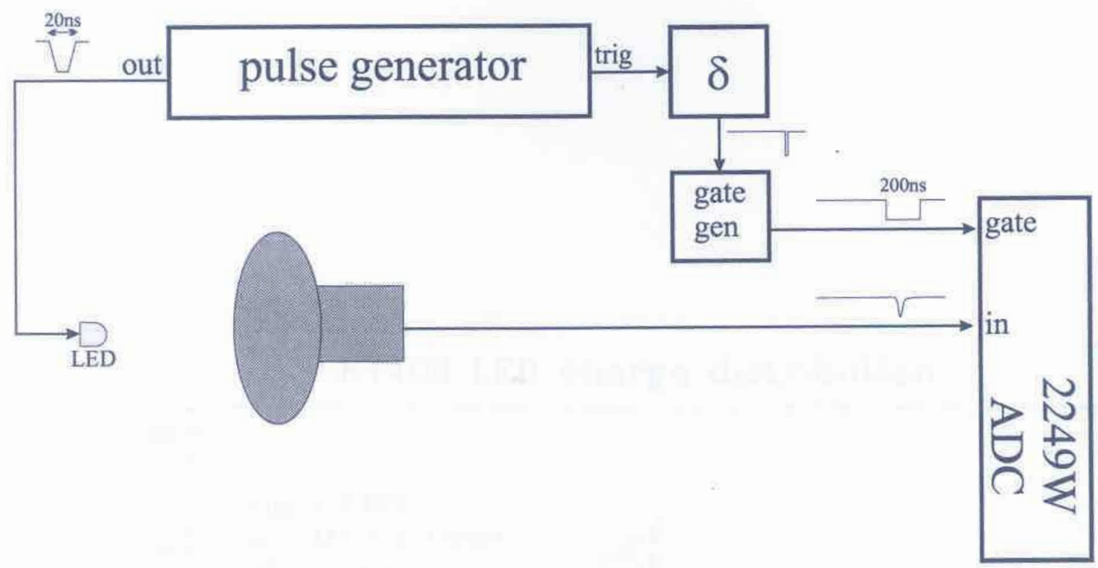

Figure 6: The test setup scheme.

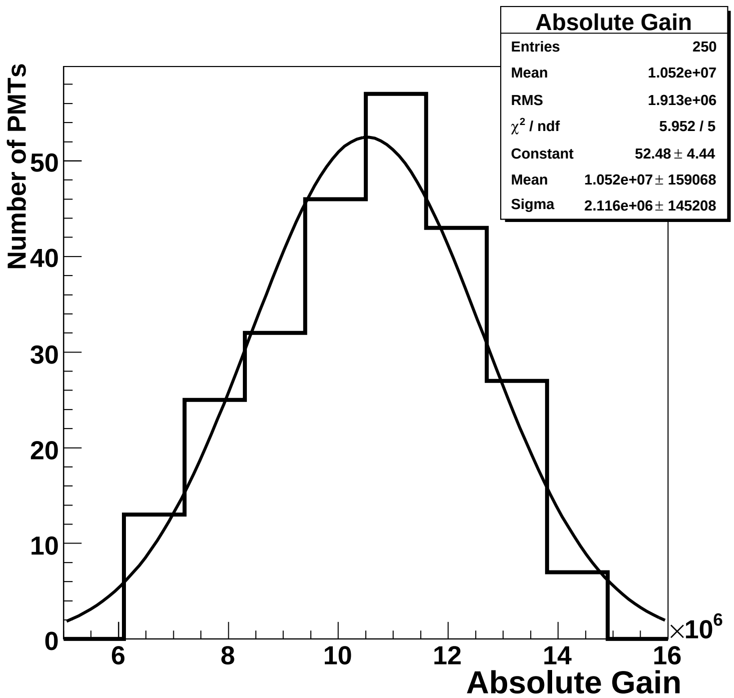

Figure 7: The PMTs gain obtained with the photo-statistics method(using the original linear bases).

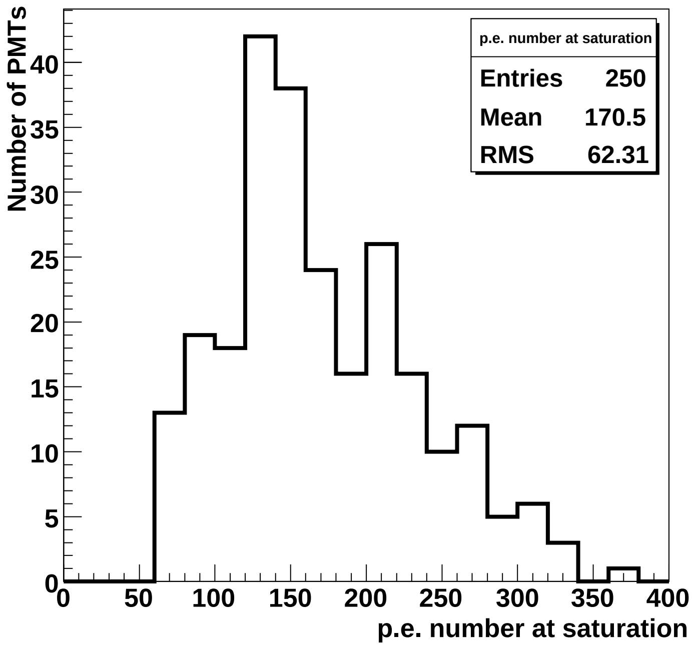

Figure 8: The PMTs saturation level obtained with the photo-statistics method(using the original linear bases).

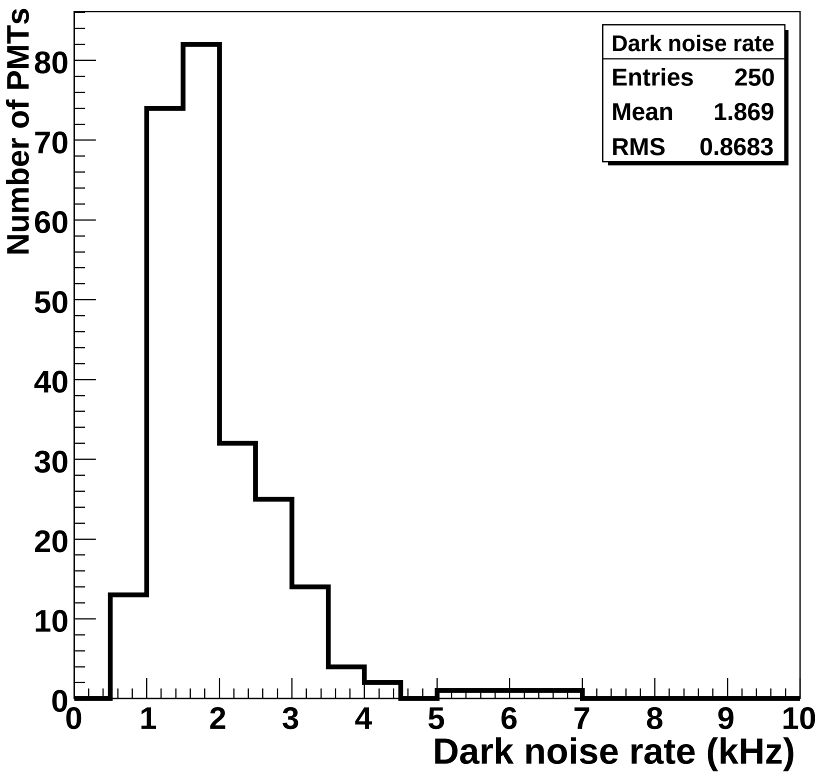

Figure 9: The dark noise rate (using the original linear bases).

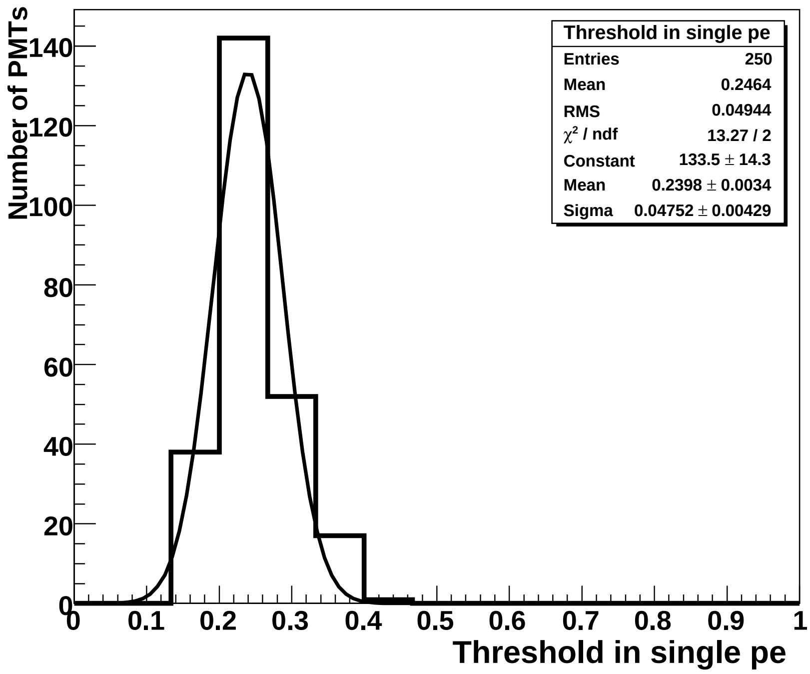

Figure 10: The threshold in spe at which was measured the dark noise rate (using the original linear bases).

4 Bases effect on the saturation performance

As I mentioned at the beginning of this report, these PMTs came with their own original linear bases and also their own original housing, after that it has been decided to use the tapered bases, the goal is to improve the saturation performance of the PMTs. There was also a few tests with a new linear bases. In the present section I will discuss the use of this kind of bases.

The figures 11 and 12 show the plot of the variance square in function of the ADC mean for two PMTs, with the new linear base and the new tapered base, its obvious that the region where the PMT response is linear dramatically extended by a factor 2 or 3. More detailed measurements, for these two PMTs, are showed in the table 2, from this table we can make two main observations: The first is about the gain, with the new bases(linear and tapered) at the same high voltage(obtained with the old linear base) the gain decreases, then we need to increase the high voltage to reach the desired gain. The second observation is related to the PMT saturation level which increased by a factor 2 at least. To confirm these observations I made measurements with more PMTs, the improvement of the saturation level(measured at the gain $\sim 10^7$) is shown in the figure 13. The figure 14 shows the new high voltage corresponding to the gain $\sim 10^7$. The difference in the gain at the same high voltage between the old linear bases and the new bases(linear or tapered) is due to the difference in their back terminations. The old linear bases, as the measurements will show later, are expected to have a 91Ω termination instead of 50Ω used for the new linear and tapered bases, and all the SHV cables used during this testing have an impedance of 50 Ω. To understand this difference in the gain, we need to remember that the base termination and the SHV cable work as current divider, like is illustrated in figure 16. The current in the input of the ADC is I_0 and it's given by the relation:

$$I_0 = \frac{R_b}{Z_0 + R_b} I_T \tag{4}$$

Where Z_0 is the SHV cable impedance, R_b is the back termination of the base and I_T is the total current. If I_T is constant, it's obvious that if we change the base termination and we keep the same cable(same impedance), the current in the input of the ADC will change and then the gain(measured at the same high voltage and for the same PMT) will change. In our case the back termination of the new tapered bases is $R_b = 50\Omega$ and for the old linear bases R_b is expected to be equal to 91Ω with 5% precision, and $Z_0 = 50\Omega$,

then the change in the gain should be:

$$\frac{Gain^{new}}{Gain^{old}} = \frac{R_b^{50}}{R_b^{91}} \frac{Z_0 + R_b^{91}}{Z_0 + R_b^{50}} = 0.775 \tag{5}$$

To confirm this explanation I show in figure 15 the gain ratio for the new tapered bases and the old linear bases, the obtained histogram is wide than expected but its most part is around the expected value corresponding to $R_b = 91 \pm 5\%\ \Omega$, the boundaries of this histogram can be understood if all the old linear bases don't have the same back termination, to confirm this hypothesis I measured the back termination for 11 old linear bases, randomly chosen, the table 3 chows the result of these measurements, as we can see the most part of the old linear bases have the expected value of the back termination of 91Ω with respect to the 5% precision, and a few old linear bases have completely different back termination, three of them have back termination $\geq 100\Omega$ and one has 62Ω back termination. Now, if we take also in account the uncertainty of the photo-statistics method, used to determine the gain, the histogram of the figure 15 becomes completely understandable. For more confirmation and comparisons I took the PMT reference (PMT# 1) and I put it under fixed high voltage, after that I measured its gain at the same high voltage but with different bases (old linear, new linear and new tapered bases), the table 4 shows the results of these these measurements, as I expected I obtained the same gain with the new linear bases and the new tapered bases because they have the same back termination, The difference in the back termination lead to difference in the measured gain not only between the new bases and the old linear bases, but also between the old linear bases themselves.
I finish this section with short remark on the improvement of the evolution of the PMT gain as function of the applied high voltage, the figure 17 shows this evolution, in log-log scale, for the old linear base and the new tapered base, the high voltage was increased from 1200 V up to 1900 V for the old linear base and up to 2000 V for the new tapered base, with a step of 100 V. As we can see the new tapered base gives better linear evolution of the gain with increased high voltage than the old linear base. Also, the fit of the measurements with the new tapered base is compatible with 13 stages amplification. In fact the gain is linked to the applied high voltage in the following way: $G = KV^{N\alpha}$, K is a constant which depends on the material of the dynodes and the voltage division between them, and α is between 0.65 and 0.75. In 13 stages PMT the gain then increases as about the 9^{th} power of the applied high voltage, doubling for each 8% voltage increase.

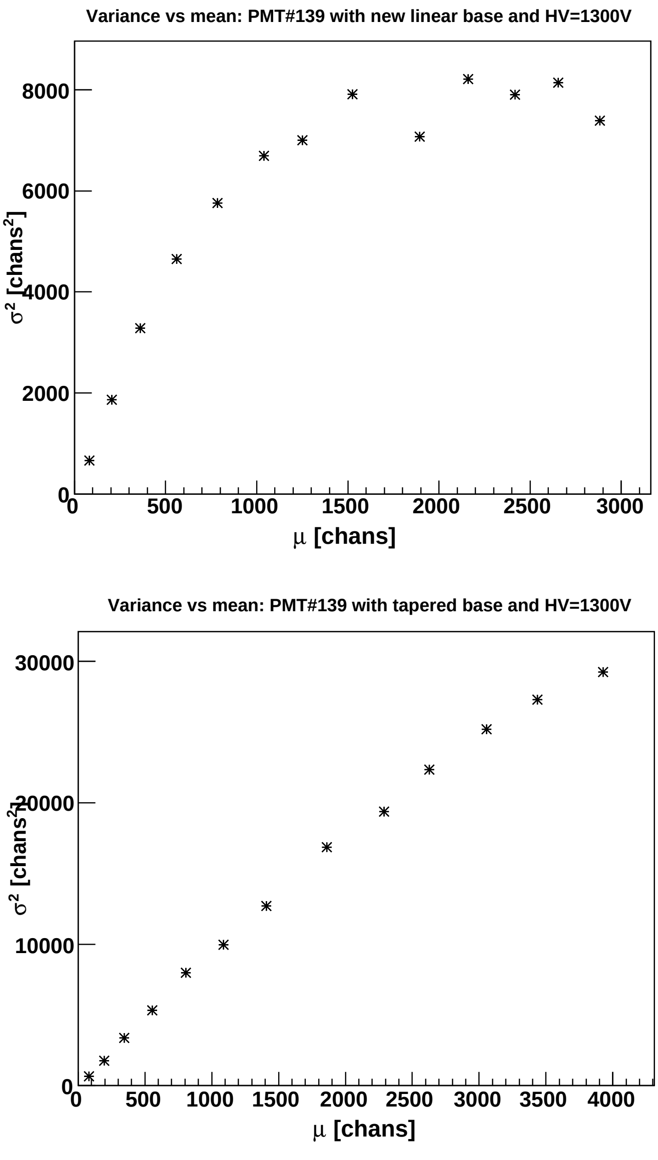

Figure 11: Evolution of the linearity of the PMT response with the new linear base(on the top), and the new tapered base(on the bottom).

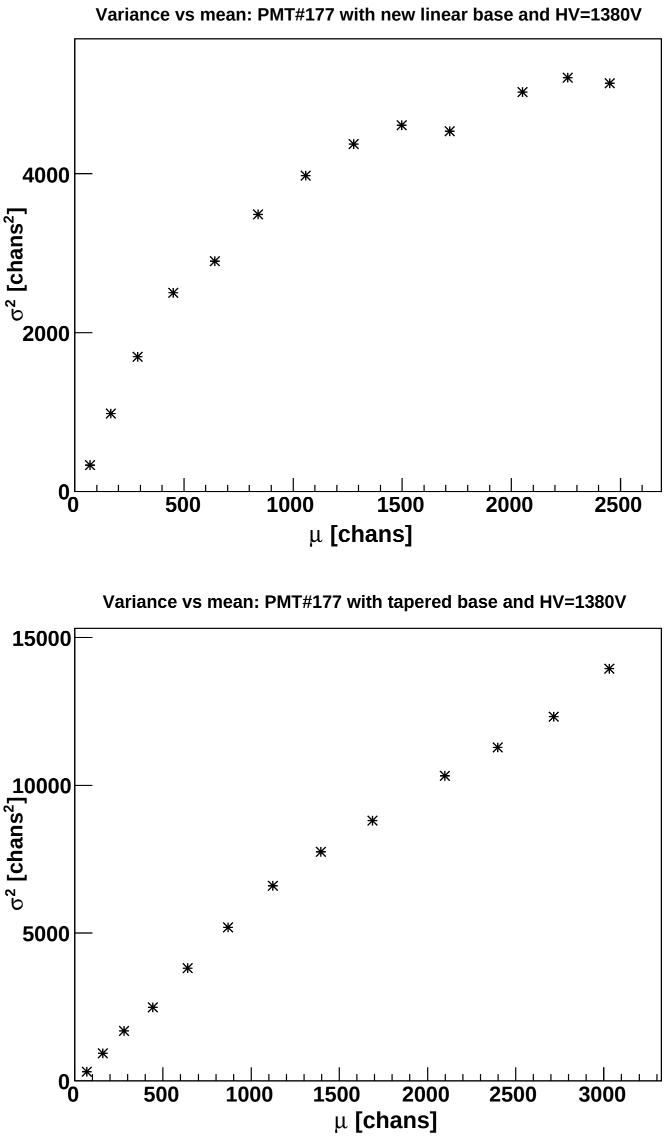

Figure 12: Evolution of the linearity of the PMT response with the new linear base(on the top), and the new tapered base(on the bottom).

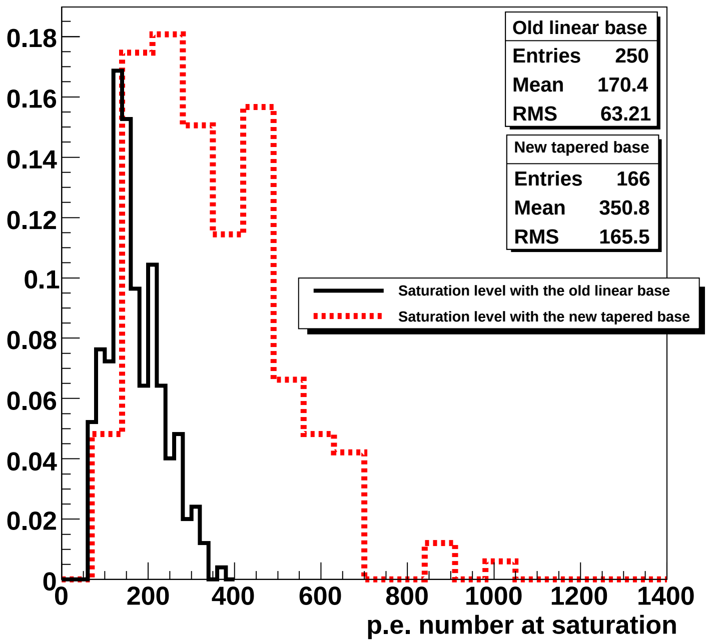

Figure 13: Comparison of the saturation performance(at the gain $\sim 10^7$) with the old linear bases and the new tapered bases.

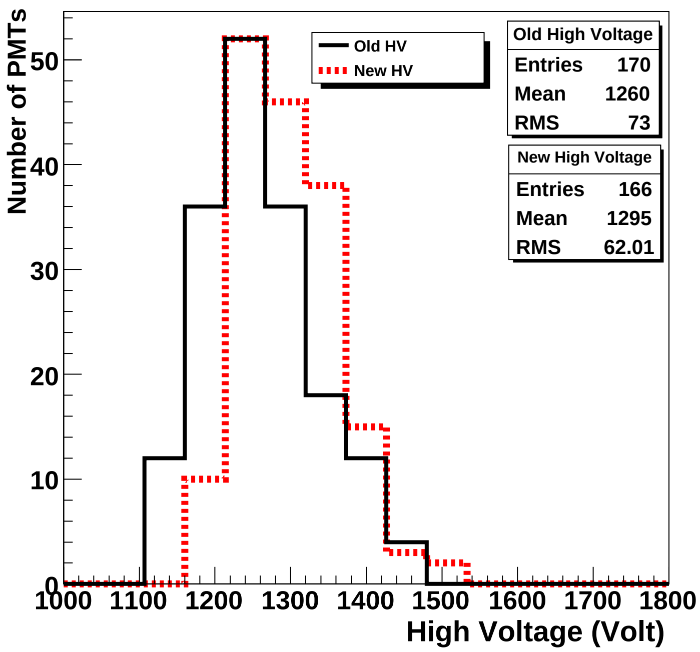

Figure 14: Comparison of the high voltage corresponding to the gain $\sim 10^7$, with the old linear bases and the new tapered bases.

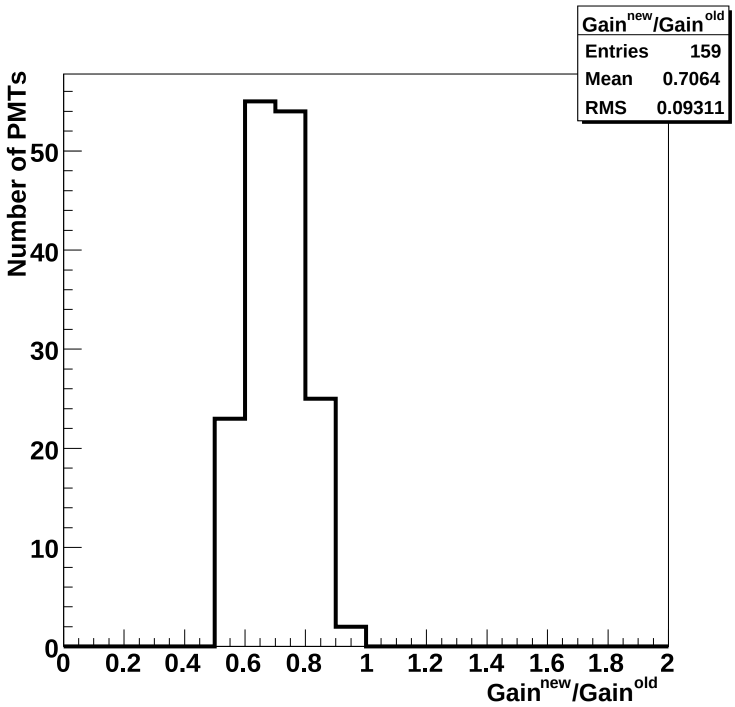

Figure 15: The ratio of the obtained gain with the new tapered base($Gain^{new}$) and the old linear base($Gain^{old}$).

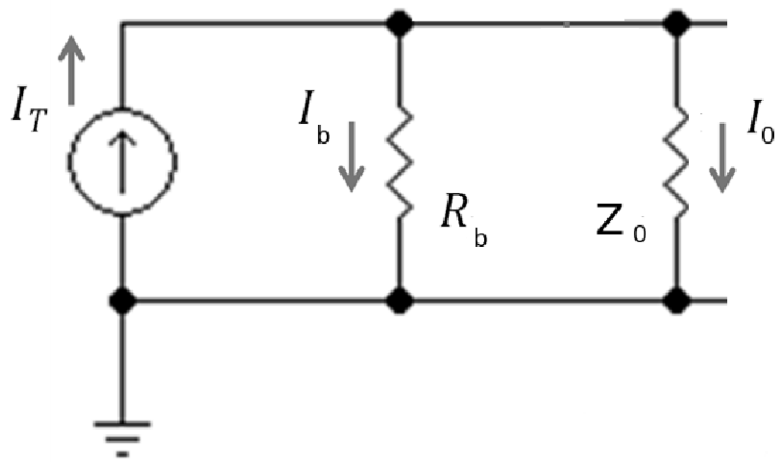

Figure 16: Current divider.

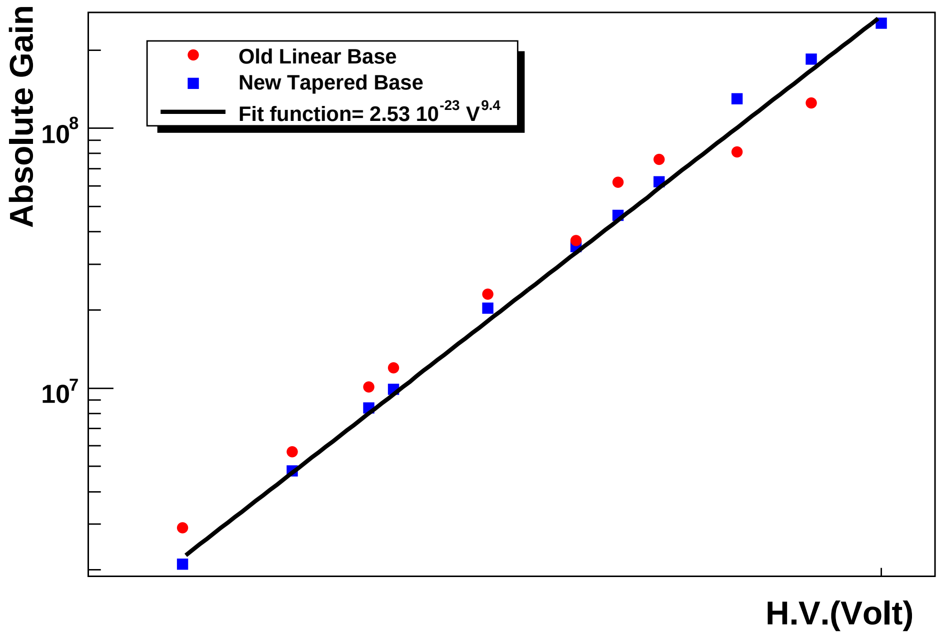

Figure 17: The absolute gain, for the PMT 1, as function as of the high voltage, the fit is for the data obtained with the tapered base.

PMT#	HV(Volt)	Abs. Gain($\sim 10^7$)	Number of pe at saturation	Dark noise rate(kHz)
PMT 139(new tapered base)	1300	1.13	508	1.6 (at 0.221 spe)
PMT 139(new linear base)	1300	1.04	189	1.7(at 0.24 spe)
PMT 139(old linear base)	1220	1.02	165	2.1(at 0.245 spe)
PMT 177(new tapered base)	1380	0.74	468	1.7(at 0.338 spe)
PMT 177(new linear base)	1380	0.71	226	1.8 (at 0.352 spe)
PMT 177(old linear base)	1380	1.16	145	2.4(at 0.215 spe)

Table 2: the performances of the new Tapered base versus the old and the new linear bases.

Base#	$R_b^{old}(\Omega)$	$Gain^{new}/Gain^{old}$
1	89	0.781
2	129	0.694
3	91	0.775
4	116	0.715
5	91	0.775
6	87	0.787
7	93	0.769
8	99	0.752
9	90	0.778
10	100	0.75
11	62	0.903

Table 3: The ratio of the obtained gain, with the new tapered base($Gain^{new}$) and the old linear base($Gain^{old}$), for different back termination(R_b^{old}) measured for different old linear bases.

5 Conclusion

Different methods were used to make the testing of 250 R1408 PMTs fast and more accurate, during this testing different type of bases were used, the new tapered bases gave good saturation performance 2 to 3 times better than the new linear bases, at the same gain(i.e. the same high voltage). However, at the same high voltage the PMT gain remains the same with the linear and the tapered bases. Based on the results of this testing, 156 PMTs were selected to be used for the inner veto of the Double Chooz detectors.

Acknowledgments

I would like to thank Prof. Charles Lane for the interesting discussions through this work.

Old linear base#	Abs. Gain(10^7)
1	1.37
2	0.89
3	1.24
4	1.09
5	1.16
6	1.5

New linear base#	Abs. Gain(10^7)
1	0.82
2	0.80

New tapered base#	Abs. Gain(10^7)
1	0.84
2	0.84
3	0.81
4	0.83
5	0.84
6	0.83

Table 4: The measured absolute gain for the same PMT at the same high voltage, but with different old linear, new linear and tapered bases.

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[3] The SuperKamiokande Collaboration, Phys. Rev. Letters 81 (1998) 1562.